Numerical Study of the Thermal Performance of Diurnal Passive Radiative Systems for Space Cooling in Owerri – Nigeria

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ABSTRACT: Passive radiative cooling does not require any energy input and has a great promise to help address global energy challenges. A 2D mathematical model based on the thermal energy balance approach was developed from the first principle and used to study the feasibility of employing the principles of passive radiative cooling for diurnal comfort space cooling in buildings. The model has been parameterized using Owerri climatic data as a typical tropical climate. The model equation was discretized in a 2D geometry of a scalable Silica-Poymethylpentene (SiO2-TPX) metamaterial with an average emissivity of 0.93 within the atmospheric window (8–13 μm) and reflectivity of 96% within the solar spectrum (0.2–3 μm) using a finite element numerical scheme. The processing was done in FlexPDE Finite Element Model Builder and Numerical Solver version 7.21/W64 3D. The temperature history, underlying energy variables, and cooling potential of the diurnal passive radiative cooler were accurately predicted from simulations for the study location. From the simulation results, which span from the hours of 6:00 a.m. to 6:00 p.m. of the day, the maximum sub-ambient temperature of the cooler was 5oC under direct solar irradiation during the day. The maximum cooling power recorded was 94 W/m2.Therefore, with the development of metamaterials, diurnal passive radiative cooling can enhance the drop in the indoor temperature of buildings when applied as direct fenestration materials, ensure net-zero energy buildings, and aid in offsetting the skyrocketing energy bills arising from increasing space cooling needs in the tropics.

KEYWORDS: Radiative Cooling, Atmospheric Window, Metamaterial, Thermal Radiation, Cooling Power, Numerical Simulation.

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1.0 INTRODUCTION

Passive radiative cooling technologies have gained research interests in recent times as a viable alternative for cooling [1]. It is simply the process by which a body loses heat by thermal radiation through the atmospheric transparency window [2]. In the case of buildings, radiative cooling results from the thermal radiation exchange between building surfaces on the Earth and the colder atmospheric layers in the sky. The general mechanism is actually by dissipating heat from buildings (heat source) to the sky (heat sink) [3]. Granqvist and Hjortsberg, [4] described passive cooling to far below ambient temperatures by using the clear night sky as a heat sink. A passive daytime radiative cooling system is made of a sky facing surface which can preserve the indoor air temperature below ambient without energy consumption by simultaneously reflecting solar radiation and emitting thermal radiation to the universe through the atmospheric window located between 8–13μm of the electromagnetic spectrum [5]. Radiative cooling occurs because the atmospheric emittance is low in the wavelength interval 8-13μm particularly if the

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air is dry. The Earth's atmosphere is relatively transparent between the wavelengths of 8-13μm. The sky is apparently transparent within this wavelength. Therefore, buildings emitting thermal radiation in this wavelength are said to be operating in what is called 'transparency window for electromagnetic waves'. This atmospheric window (8-13 μm) in the earth's atmosphere that cannot capture infrared light, corresponds to the peak thermal radiation spectrum of terrestrial objects near ambient temperature (~300 K). Within this transparent window, objects on the earth can radiate heat into the cold outer space, thereby reducing their own temperature. This window allows the radiation emitted by the earth to escape to space with no absorption within the atmosphere. It is a cooling technology that requires no energy input while presenting a reduction in energy demands and environmental pollution. Most of the cooling methods employed in the past have always required energy or resources to assist the heat dissipation, while radiative cooling is a natural cooling method on the Earth. The need for cooling is greatest during the day. This is especially so in tropical climates where temperatures are relatively so high during the day for most part of the year, hence the consideration of diurnal radiative cooling. In some cities, such as Philadelphia, cooling represented 74 % of peak electricity demand on an extremely hot day [6].

Zhou et al., [7] reviewed the concept of radiative cooling from the lenses of different authors and researchers. Unlike traditional cooling techniques, radiative cooling does not require electricity to operate, making it particularly appealing for reducing energy demand for cooling while also addressing global warming by lowering carbon emissions. It is a basic principle that a radiative cooler must be thermally emissive in order to dissipate heat through thermal radiation. During the day, the cooler must minimize the solar heating effect in order to maintain sub ambient temperatures. This view is shared by Li et al, [8] who stated that for high performance radiative cooling to take place, thenP_{rad}(heat radiated by the RC) must be maximized and $P_{sun}, P_{atm,}$ and $P_{cond+conv}$(solar irradiance, atmospheric radiation and heat loss due to conduction and convection) minimized. This phenomenon is however material dependent which implies that not all materials have the physical, chemical and intrinsic property to achieve radiative cooling. Researchers have created a variety of materials with engineered optical, thermal, and mechanical properties based on these criteria. Lin et al, [9] in his research work developed an all-inorganic efficient narrowband emitter for daytime radiative cooling. The device showed strong solar reflection (96%) and highly selective IR emission ($\varepsilon_{8-13\mu m} = 96.6\%$) within an atmospheric window, rendering it quite suitable for cooling radiatively in hot humid climatic regions. Heng Luo and Weizhi Zou, [10] researched on UV cured coatings for highly efficient passive all day radiative cooling. The author presented a fast, low-cost, and scalable UV-curing method for producing porous polymer coatings via photopolymerization-induced phase separation. Using trimethylolpropane triacrylate (TMPTA) and vinyltriethoxysilane (VTES) as a formulation, the resulting poly (TMPTA-VTES) coating has a hierarchical pore structure, resulting in an excellent passive all-day radiative cooling capability. A data logging solar power meter was used to measure solar irradiance, and a hygrometer was used to measure relative humidity. They automatically tracked the data every 60 seconds. The data obtained showed significant radiative cooling capacity. Hossain and Gu [11] researched on the use of ultra-white $BaSO_4$Paints and Films for daytime sub-ambient radiative cooling. It was shown that the $BaSO_4$ nanoparticle film and $BaSO_4$-acrylic nano composite paint can provide full-daytime radiative cooling. With the $BaSO_4$ nanoparticle film, a high solar reflectance of 97.6% and a high sky window emissivity of 0.96 were achieved by using an appropriate particle size and a broad particle size distribution. On-site field tests show surface temperatures more than 4.5 degrees Celsius below ambient, or an average cooling power of 117 W/m^2, which is among the highest cooling power reported. To improve coating reliability, a 60% volume concentration of $BaSO_4$-acrylic paint is used. Fu et al., [12] did an extensive research of polymer coating with gradient dispersed dielectric nanoparticles for enhanced daytime radiative cooling. The author presented a modified Monte-Carlo method for investigating the spectral response and cooling performance of polymer coatings with gradient dispersed nanoparticles. Using this method, he conducted a quantitative analysis of the solar reflectance, infrared emittance, and cooling power of four types of gradient structures.

Different mechanisms of radiative cooling have been highlighted which includes; spectral selectivity, constructive or destructive interference, photonic crystals, Meta-surfaces, porous polymers, paints and pigments. The areas of application of radiative cooling as detailed by the author includes; building, semiconductor devices, personal thermal management. Radiative cooling is also a green technology, which does not require ozone depleting refrigerants in operation. Suhendri et al, [13] carried out review research on the Implementation of Passive Radiative Cooling Technology in Buildings. Buildings with RC have been prototyped in a variety of ways. When RC is combined with other cooling technologies, design options become even more numerous. However, an architectural analysis of the RC systems should be performed before it is widely accepted by the architectural community as one of the promising passive design strategies for sustainable buildings. Precedents of architectural features involved in RC passive application proposals must be examined. In theory, the roof is the best place to put an RC emitter when compared to other building envelopes such as walls and paints.

Jeong et al [5] stated that diurnal radiative coolers can be used in integration with HVAC systems considering the steady state energy balance within the radiative cooling panel integrated HVAC systems. For instance the cooling performance and indoor air temperature as evaluated by numerical analysis revealed that a 100 m^2 passive radiative cooling panel could chill water for the cooling of air, reducing indoor air temperature by 10°C, equivalent to a net cooling power of 1600W and study suggests that the proposed passive radiative cooling system should also as such, be used to pre-cool the ambient hot air such that the overall energy consumption of a traditional air-conditioning system can be reduced. The findings promise the application of passive daytime radiative cooling in building HVAC systems.

Despite the advantages that radiative cooling offers, the techniques and approaches have not been generally and extensively adopted in buildings. The difficulties encountered so far range from technical to financial and even geographical constraints. In general, the performance of radiative coolers or radiative cooling panels is strongly reliant on the climate and geographical factors. Many suggestions for the use of radiative cooling in buildings are still in the research and development stage, and they mostly revolve round the emitter material or the use of radiative cooling to supplement active cooling technologies [14]. Sub-ambient cooling can be achieved through radiative coolers that selectively emit radiation within this atmospheric window (8–13μm) to outer space and suppress absorption/emission of other wavelengths. If a surface benefits from daytime radiative cooling, its equilibrium temperature will be lower. This can be achieved only if about 85% of solar radiation within the visible and near-infrared spectrum is reflected [15]. Despite the challenges faced by the radiative cooling technology, recent advances in the science of materials with favourable radiative cooling properties has reignited interest in radiative cooling as a potentially viable alternative for lowering space cooling energy consumption. Jay Prakash Bijarniya, [16] in his work on the Performance simulation of polymer-based nano particle and void dispersed photonic structures for radiative cooling posited that passive radiative cooling is a new field that requires further material development. Hence, before fabrication, the computational approach for effective metamaterial design must be established. The finite difference time domain (FDTD) method is an intriguing numerical strategy to investigate Interaction of electromagnetic waves with the material. He simulated and reported the behavior of various nanoparticles (SiO_2, TiO_2, Si_3N_4) and void dispersed polymers for the solar and thermal infrared spectrums using the FDTD method. The author proposed an algorithm for simulating the surface emissive properties of various material nanostructures in both the solar and thermal infrared spectrums, followed by the estimation of cooling performance. In a typical hot summer clear day in Varanasi, India, the maximum cooling power of 162 W/m^2 at ambient temperature is observed for Si_3N_4 with voids inline structure during evening time when solar gain reduces to zero, and 132 W/m^2 cooling power is observed for SiO_2 with the silver layer in staggered structure during peak solar radiation. Due to hot summer days, having elevated ambient temperature leads to the emission of fourth power to absolute temperature. A maximum temperature drops of

9.5°C during the night and 7.5°C during the daytime performance is observed.

Han et al, [17] carried out a preliminary study of passive radiative cooling under Singapore's tropical climate through both numerical and experimental approaches, to investigate the feasibility of using radiative cooling in Singapore's hot and humid climate. To obtain the cooling power of the radiative cooler while considering different solar spectral irradiance and total water vapor column, a theoretical simulation based on the heat transfer balance is first proposed. The higher solar irradiance in Singapore, particularly in the UV and VIS spectrums where material absorbance is relatively high, may negate any cooling effects. Furthermore, the increased atmospheric radiation caused by Singapore's higher humidity and ambient temperature may degrade cooling performance. According to the net cooling power calculated using the heat transfer balance model, the radiative cooler could not produce cooling power during the day. Cooling was possible at night and was primarily influenced by the total water vapor column. Wang et al [18] carried out a modeling of the photonic radiative cooler and the simulation of a system that integrates the photonic radiative cooler with radiant floor cooling in a medium office building. The system was simulated with Energy Plus and the extensive use of its energy management system module. The simulation results show that the radiator surface temperature remains well below the ambient air temperature even during summer in Las Vegas. The radiative cooler was sufficient to meet the cooling load for five months of the year and addressed at least 17% of the total hydronic loop load in the peak summer months.

This study aims to evaluate the potential and performance of passive radiative cooling system in tropical climates, as well as the technological solution of providing free cooling energy to offset or augment mechanical cooling in buildings using numerical analysis.

2.0 Physical Model of the Diurnal Passive Radiative Cooling (DPRC) System

The modelled DPRC is as shown in Figure 1.

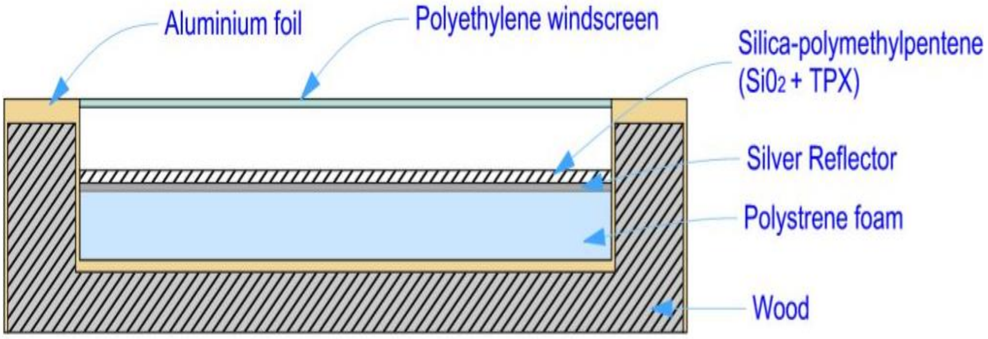

Figure 1 Configuration of the Modelled Photonic Cooler

The radiative cooler is characterized by very high reflectivity in the solar band and high emission of thermal radiation in the atmospheric spectrum. Figure 1 consists of a frame which serves as a support for the system while also serving the purpose of mitigating against heat gains from the surroundings through conduction and convection. The frame is made of wood which is a poor conductor of heat but also covered with sheets of Aluminum foils, a very reflective material in order to protect the wooden frame from radiation. It also has a randomized hybrid metamaterials which comprises a 50 μm thick Silica-Polymethylpentene (SiO_2+TPX) film containing 6 % by volume of randomly distributed silicon dioxide microspheres deposited on top of a 200 nm silver (Ag) reflector. The dimension of the emitter is 360 × 260 mm. The emitter and reflector sit on polystyrene foam serving as an insulator for the emitter. A low-density polyethylene film is placed 200 mm above the emitter to serve as an infrared-transparent windshield because of its transparency across the entire solar and atmospheric window bands.

3.0 Modelling and numerical simulation

In order to develop the mathematical models, the following assumptions were made to simplify the heat transfer processes for the formulation of equations governing energy interactions in the system.

i. The radiative cooler is considered a single control volume with a negligible thermal capacitance.
ii. The heat transfer is a two-dimensional heat exchange. This is so because the radiative panel is taken to be of very minimal small thickness.
iii. There is no internal heat generation in the system.
iv. The material's thermo-physical properties do not vary with temperature. The thermo-physical properties of materials actually vary with temperature but this variation is not significant enough to tangibly alter their performance in the system and temperature range under study.
v. Only the top heat losses are accounted for. It is assumed that the edge and bottom of the RC system are sufficiently insulated and thus edge and bottom heat losses are considered negligible.

Using the control volume approach (Figure 3) and the above assumptions, energy and mass balance equations governing the functioning of the DPRC system were formulated.

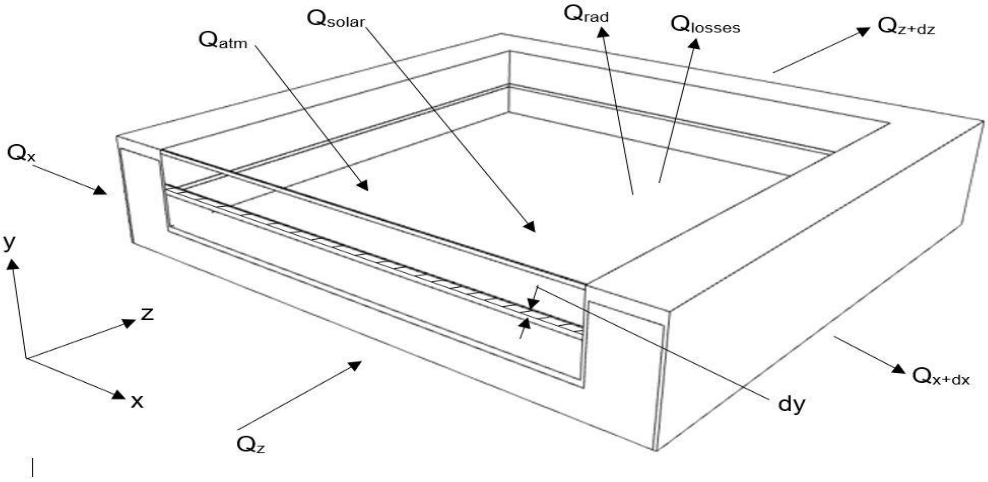

Figure 2 Schematic illustration of the Control Volume

Considering the control volume of the DPRC system as shown in Figure 2, with dimensions $dx, dy, and\ dz,$ the general energy for the system is a statement of the law of conservation of energy which can be expressed as follows:

$$Energy\ flux\ into\ the\ control\ volume\ +\ Internal\ Heat\ generation\ in\ the\ control\ volume\ =\ Energy\ flux\ out\ of\ the\ control\ volume\ +\ Rate\ of\ increase\ in\ internal\ Energy\ of\ the\ control\ volume \tag{1}$$

$$Q_x + Q_z + Q_{solar} + Q_{atm} + Q_{i.gen} = Q_{x+dx} + Q_{z+dz} + Q_{rad} + Q_{losses} + Q_{int} \tag{2}$$

Where Q_x is the energy flux into the control volume in the x - direction, Q_z energy flux into the control volume in the z – direction, Q_{solar} is the incident solar radiation on the RC system, Q_{atm} absorbed atmospheric downward radiation on the RC system, $Q_{i.gen}$ is the internal heat generation in the RC system, Q_{x+dx} is the thermal energy leaving the control volume in the x – direction, Q_{z+dz} is the thermal energy leaving the control volume in the z – direction, Q_{rad} + is the heat radiated by the cooler, Q_{losses} is the total heat losses and Q_{int} is the time rate of change in the internal energy of the RC system.

The thermal energy flux into the DPRC system for a 2-D conduction in the x- and z- directions as obtained by Fourier's law is given below as:

$$Q_x = -K_x dydz\frac{\partial T}{\partial x} \tag{3}$$

$$Q_z = -K_z dydx\frac{\partial T}{\partial z} \qquad (4)$$

Making Reference to assumption iii, there is no internal heat generation. Thus $Q_{i,gen} = 0$

Also, for a 2-D conduction in the DPRC system, thermal energy flow out of the system in the x- and z – directions are given as:

$$Q_{x+dx} = Q_x + \frac{\partial Q_x}{\partial x}dx \qquad (5)$$

$$Q_{z+dz} = Q_z + \frac{\partial Q_z}{\partial z}dz \qquad (6)$$

Q_{losses} = Overall, heat loss from the surface

$$Q_{losses} = [U_L(T - T_a)] \qquad (7)$$

Where U_L the overall heat is transfer coefficient from the radiative panel to the ambient and T_a is the ambient temperature

Substituting Eqs 3-7 into Eq 1 and simplifying, the equation for conservation of energy in the DPRC system can be written as:

$$-K_x\left(\frac{\partial T}{\partial x}\right)dydz - K_z\left(\frac{\partial T}{\partial z}\right)dxdy + Q_{solar}\,dxdz + Q_{atm}\,dxdz =$$
$$-K_x\left(\frac{\partial T}{\partial x}\right)dydz - \frac{\partial}{\partial x}\left(K_x\frac{\partial T}{\partial x}\right)dxdydz - K_z\left(\frac{\partial T}{\partial z}\right)dxdy - \frac{\partial}{\partial z}\left(K_z\frac{\partial T}{\partial z}\right)dxdydz + Q_{rad}\,dxdz + [U_L(T - T_a)]dxdz +$$
$$\rho_e c_e \frac{\partial T}{\partial t}dxdydz \qquad (8)$$

From Fig. 3, dy is the thickness of the emitter which can be designated as δ_e. Simplifying and dividing through by $dxdz$, Eq. 8 becomes:

$$\rho_e c_e \delta_e \frac{\partial T}{\partial t} = \left[K_x\left(\frac{\partial^2 T}{\partial x^2}\right) + K_z\left(\frac{\partial^2 T}{\partial z^2}\right)\right]\delta_e + Q_{solar} + Q_{atm} - Q_{rad} - U_L(T - T_a) \qquad (9)$$

The material of the DPRC system is a homogenous material and its thermal properties are independent of temperature. Hence, Eq (6) simplifies to:

$$\rho_e c_e \delta_e \frac{\partial T}{\partial t} = K_x\,\delta_e\left[\left(\frac{\partial^2 T}{\partial x^2}\right) + K_z\left(\frac{\partial^2 T}{\partial z^2}\right)\right] + Q_{solar} + Q_{atm} - Q_{rad} - U_L(T - T_a) \qquad (10)$$

The solar radiation absorbed by the RC panel or the rate at which radiant energy (irradiation) is absorbed from the sun per unit surface of the radiative material area is given as [19]:

$$Q_{solar} = \phi\alpha_e\tau_{ws}\rho_r.G.A_s \qquad (11)$$

Where ϕ is the angle of inclination of the RC panel,$\alpha_e$is the absorptivity of the emitter, τ_{ws} is the transmissivity of the RC windscreen, ρ_r= reflectivity of the reflector and G is the incident solar radiation on the RC panel, and, A_s = Area of the emitter surface.

The rate of solar radiation incident on an extraterrestrial horizontal surface parallel to the ground at a given time of the year is given by:

$$G = G_{sc}\left[1 + 0.033\cos\left(\frac{360N}{365}\right)\right][\cos(L)\cos(\delta)\cos(h) + \sin(L)\sin(\delta)] \qquad (12)$$

Where G_{sc} is the solar constant, N is the Day number L is the Latitude of the location, δ is the Solar declination and h is the hour angle.

The solar declination, δ for any day of the year can be calculated by the following equation:

$$\delta = 23.45 \sin\left[\frac{360}{365}(284 + N)\right] \tag{13}$$

The heat flux radiated by a real surface is given by the following equation [20]:

$$Q_{rad} = \varepsilon_e \sigma T^4 \tag{14}$$

Where ε_e the emissivity of the radiative cooling system, T_s is the temperature of the surface of the RC panel and σ is the Stefan – Boltzman constant.

The radiation from the atmosphere (sky) onto the RC panel is given as [20]:

$$Q_{atm} = \varepsilon_{sky} \sigma T_{sky}^4 \tag{15}$$

Where ε_{sky} is the emissivity of the sky and T_{sky} is the temperature of the sky at a given time

Based on assumption (v), the total heat loss from the radiative cooling system has one basic components: top heat losses through the windscreen. According to Nwaji [21] and Kalogirou [22], the top loss heat transfer coefficient for a RC system can be obtained through the following equation

$$U_L = \left[\frac{N_{ws}}{\frac{C}{T}\left[\frac{T-T_a}{N_{ws}-f}\right]^{0.33}}\right]^{-1} + \frac{\sigma(T^2 + T_a{}^2)(T+T_a)}{\frac{1}{\varepsilon_{rc}+0.05N_e(1-\varepsilon_e)}+\frac{2N_e+f-1}{\varepsilon_{ws}} - N_{ws}} \tag{16}$$

Substituting Eq 16 into Eq 7, we have that the Overall heat transfer is given as

$$Q_{losses} = \left(\left[\frac{N_{ws}}{\frac{C}{T}\left[\frac{T-T_a}{N_{ws}-f}\right]^{0.33}}\right]^{-1} + \frac{\sigma(T^2 + T_a{}^2)(T+T_a)}{\frac{1}{\varepsilon_{rm}+0.05N_e(1-\varepsilon_e)}+\frac{2N_e+f-1}{\varepsilon_{ws}} - N_{ws}}\right)(T - T_a) \tag{17}$$

$f = (1 - 0.04h_w + 0.0005h_w^2)(1 + 0.091N_{ws})$ and

$C = 365.9(1 - 0.00883\phi + 0.0001298\phi^2)$

Where N_{ws} is the number of windscreen covers, N_e is the number of Emitters, ε_{ws} is the Emissivity of the windscreen, ε_e is the emissivity of the radiative cooler (emitter), σ is the Stefan-Boltzman constant and ϕ is the angle of inclination of the RC panel.

For a DPRC system with a single polyethylene film windscreen, the convective heat transfer coefficient due to wind is given by Mingke et al [23] in the equation below

$$h_w = 0.5 + 1.2u^{0.5} \tag{18}$$

Where u is the prevailing windspeed of the location under study

According to Anyanwu and Iwuagwu [24], the average wind speed for the study location, Owerri, Nigeria is given as 2.80 ± 0.81m/s

According to Mirzabozorg et al [25], the ambient temperature can be evaluated per time to an acceptable degree of accuracy using the sinusoidal function as follows

$$T_a(t) = \bar{A} \sin\left(\frac{2\pi(t-\xi)}{P}\right) + B \tag{19}$$

Where $\bar{A}$ is the amplitude, B is the annual mean temperature, t is the time in day, ξ is time in day in which $(\xi) = B$, and P is period of sine function, which is 365 days. A can be obtained as follows

$$A = \frac{1}{2}\left(|T_{max} - T_{mean}| + |T_{min} - T_{mean}|\right) \qquad (20)$$

Where

$$T_{max} = \frac{\sum_{i=1}^{n}(T_{max})_i}{n},$$

$$T_{min} = \frac{\sum_{i=1}^{n}(T_{min})_i}{n},$$

$$T_{mean} = \frac{\sum_{i=1}^{p} T_i}{p},$$

Where n is the number of days of the month
The input parameters for the simulation are given in Table 1.

Table 1: Model input parameters

Parameter /Symbol	Value	Unit
Latitude of Owerri	5.48	o
Sky emissivity for Owerri	0.68	
Mean Daily relativeHumidity in Owerri, RH	0.87	
Dry Bulb temperature of Owerri, T_{db}	298.5(25.5°C)	K
partial pressure of water vapor present in the atmosphere for Owerri, P_w	28.16×10^{-3}	Bar
transmissivity of the windscreen	0.82	
Emissivity of the windscreen	0.96	

4.0 RESULTS AND DISCUSSION

A finite element numerical solution methodology was applied to simulate the thermal performance of the system using a scripted FlexPDE finite element model builder and numerical solver version 7.2. The model was parameterized using the climatic data of Owerri, Nigeria. The simulation was carried out for the time period between 06:00 hours to 18:00 hours of the test day. The model results have been compared with the preliminary results of an experiment from a similar work carried out in the study location as shown in Fig. 3.

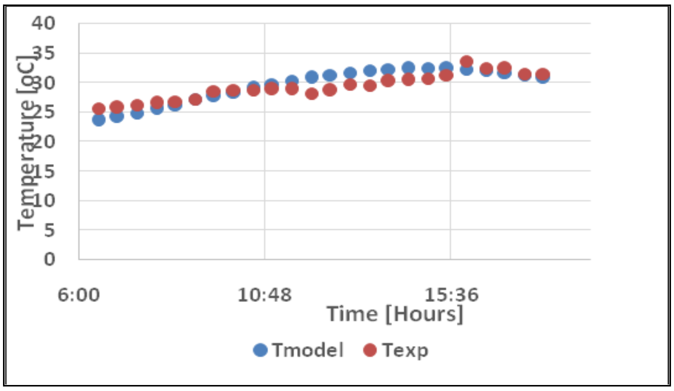

Figure 3 Validation of model results

From Figure 4, the temperature contour shows that most of the incident solar radiation is reflected away almost uniformly from the emitter surface. However, this is not as pronounced at the edges of the DPRC. This can be attributed to the effect of the insulating materials on the surfaces exposed directly to the insulators as the insulation does not permit reflection through them or their direction. The surface temperature plot of Figure 5 is a 2-D topographic display of the temperature along the x and y axis of the cooler and it shows that it is only in the y-direction that temperature increases significantly in the cooler.

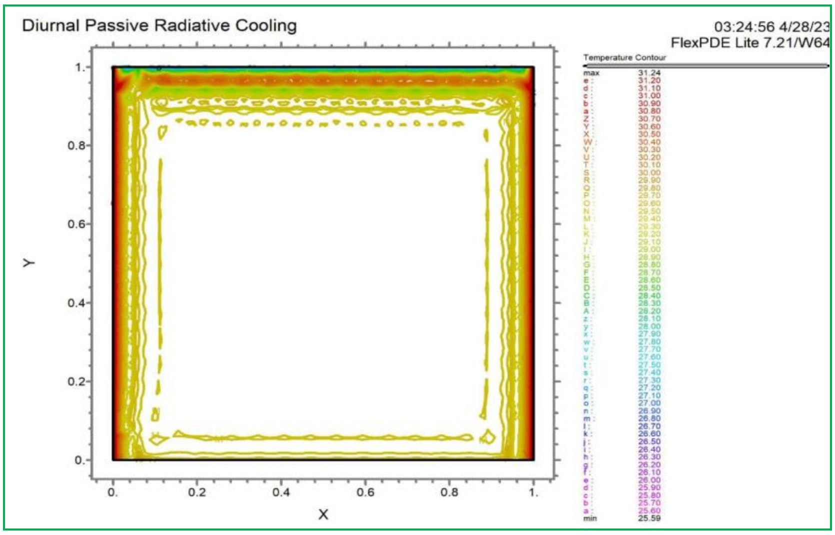

Figure 4 Temperature Contour along the RC during Diurnal Cooling

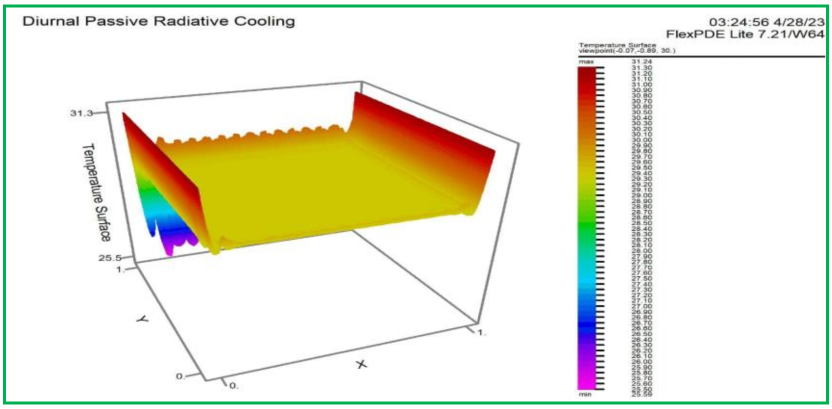

Figure 5 Surface Plot of Temperature Distribution in the RC Panel during Diurnal Cooling

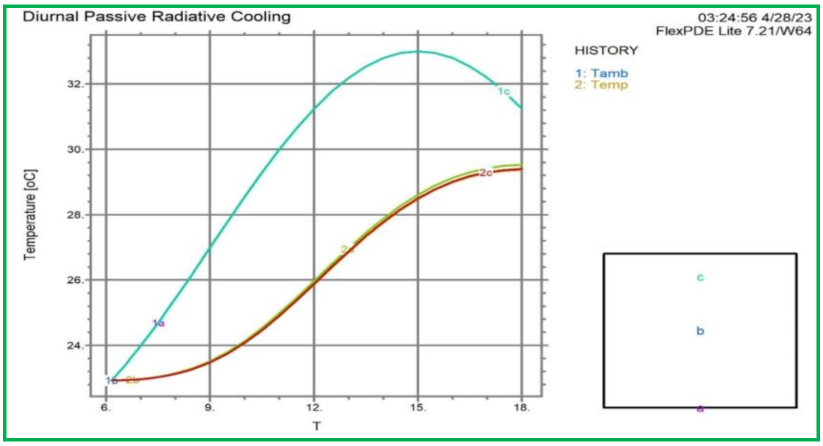

Figure 6 Comparison of the Ambient Temperature with the Cooler Temperature

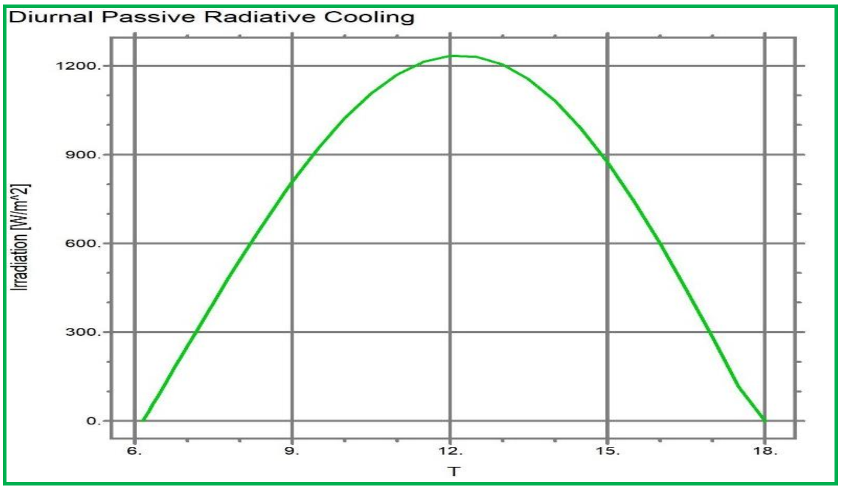

Figure 7 Incident Solar Radiation on the RC

Figure 6 and 7 shows the plot of the predicted ambient and cooler temperatures and solar irradiation for Owerri in the month of January for the daytime hours from 6:00 hours to 18:00 hours. Figure 6 shows that the ambient temperature value rose from 23°C at 06:00 hours to a maximum of 33°C at 15:00 hours, and thereafter decreased slowly to 31.2°C at 18:00 hours, while the cooler temperature remained fairly below ambient throughout the simulation period. The highest temperature difference between the ambient temperature and that of the cooler was 5°C which was observed at 12:00 hours. Fig. 7 shows the predicted solar irradiation on the surface of the radiative cooler for the day. This shows that at sunrise, the surface of the DPRC system begins to receive solar radiation from the sun which rises to a peak value of 1250 W/m^2 at 12:00 hours. After this time, the irradiation begins to drop even though the ambient temperature is still rising for the next three hours. The irradiation drops progressively till sunset at about 18:00 hours. Since at peak sunlight, the cooler surface remained below ambient, it can be concluded that the Silica- Poymethylpentene is a fairly good diurnal passive radiative cooler material.

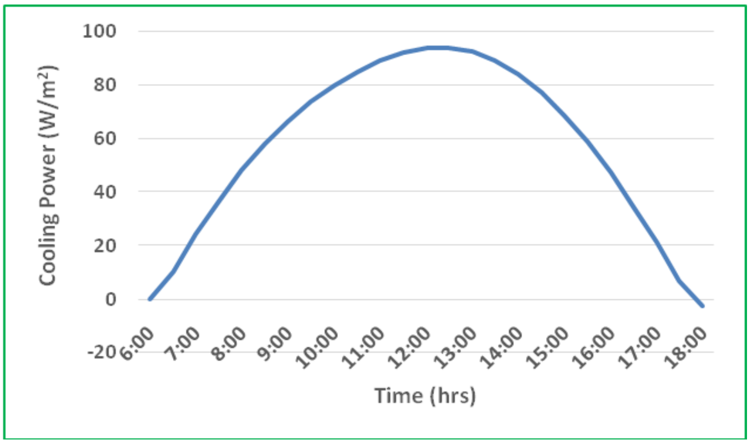

Figure 8 Cooling Power Curve

Figure 8 shows the predicted cooling power of the Silica-Poymethylpentene DPRC system for the month of January. It can be observed that upon sunrise, the cooling power of the system rises progressively to a peak value of 94 W/m^2 for the day at 12:30 hours which coincides with the period of peak solar irradiation. After this period, the cooling power falls progressively till no cooling is observed again at 18:00 hours corresponding to the time where there is no solar radiation. It is observed that at the time of peak solar irradiation (12:00 hours), the cooler temperature showed its highest variation with the ambient temperature at 5°C difference which indicates that the RC system is very reflective in the solar band. The system showed significant cooling power throughout the duration of sunshine with its peak coinciding with the time of peak solar irradiation.

4. CONCLUSION

The simulation of the Silica-Poymethylpentene diurnal passive radiative cooling system based on a 2D model of the system setup has been carried out. It is done to investigate the performance of the radiative cooling system for daytime operations in Owerri, Nigeria, a typical tropical climate. The results clearly show that the system showed appreciable cooling during the day, indicating that diurnal radiative cooling is feasible as the radiative cooler showed sufficient cooling potential under direct sunlight. From the simulation results, which span from the hours of 6:00 a.m. to 6:00 p.m. of the day, the maximum sub-ambient temperature of the cooler was 5oC under direct sunlight. The maximum cooling power recorded was 94 W/m2. Therefore, with the development of metamaterials, diurnal passive radiative cooling can enhance the drop in the indoor temperature of buildings when applied as direct fenestration materials, ensure net-zero energy building, and aid in offsetting the skyrocketing energy bills due to rising space cooling needs in the tropics.

NOMENCLATURE

c	Specific heat capacity [kJ/kg]
G_{sc}	Global Solar constant [W/m^2]
k	Thermal Conductivity of the Emitter [W/mK]
U_L	Overall heat transfer coefficient [W/m^{2}K]
u	wind speed [m/s]
T	Temperature
T_a	ambient temperature
Q_{solar}	Incident solar radiation
Q_{atm}	Atmospheric radiation
ρ	Reflectivity,
ε	Emissivity
Φ	Angle, ^{o}
α	Absorptivity
τ	Transmissivity
δ	thickness
σ	Stefan-Boltzman Constant

Subscripts

a	ambient
atm	atmospheric
e	emitter
ins	insulation
rad	radiated
s	surface
sur	surrounding
ws	windscreen

Abbreviations

HVAC	Heating Ventilation and Air-conditioning
DPRC	Diurnal Photonic Radiative Cooler
IR	Infrared
PE	Polyethylene
RC	Radiative Cooling
UV	Ultraviolet
TPX	Polymethylpentene
PMMA	Polymethyl Methacrylate

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